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# HUMAN CONTROL PERFORMANCE AND TOLERANCE UNDER SEVERE COMPLEX WAVE FORM VIBRATION, WITH A PRELIMINARY HISTORICAL REVIEW OF FLIGHT SIMULATION

by Carl C. Clark, Ph.D.
Manager, Life Sciences Department
Martin Company
Baltimore 3, Maryland

## Introduction

As man travels, he vibrates. For as he travels, he generally experiences accelerations not perfectly uniform in magnitude nor direction, and these he feels as varying forces or vibrations. As he first travels faster, these vibrations become more severe, until he learns new ways to reduce them: the clearing of foot paths, the paving of roads, the welding of railroad tracks, the use of gust alleviation autopilot controls in aircraft, the improved spacecraft "adapter ring" attachment fairings to reduce trans-sonic buffet of multi-stage rocket vehicles. We will insure that the grandmothers, going to tea, booming across the oceans in rockets, will have smooth trips. But the pioneers, the pathfinders, will vibrate, while travelling faster on or near the earth, or penetrating through the atmosphere, or using thrust.

What can we do, preparing for these pioneers, to insure that these expected vibrations will not jeopardize their lives nor their missions? This paper will describe one approach, of attempting to simulate the expected and more than the expected complex wave form vibrations to determine tolerance and pilot control capabilities, to attempt to find solutions in simulation before the first flights in reality. The experimental work to be described was done in November, 1959, and June, 1960, on the Johnsville Navy human centrifuge, at the Aviation Medical Acceleration Laboratory, U.S. Naval Air Development Center, Johnsville, Pennsylvania, and in June, 1960, on the North American "G-seat", the vertical accelerator of the North American Aviation Co., Inc., Columbus, Ohio, while the author was Jostle Program Officer at the Aviation Medical Acceleration Laboratory. The experimental work was the subject of the confidential reports NADC-MA-L6005 and NADC-MA-6128, U.S. Naval Air Development Center, and NA60H-444, North American Aviation, Inc., Columbus. Unclassified aspects can now be reported.

Use of these large simulator facilities can only be made with the cooperation of many people. Particular acknowledgement is expressed for the efforts of Capt. F. K. Smith, MC, USN, and Mr. Robert Snyder, Aviation Medical Acceleration Laboratory, U.S. Naval Air Development Center, Harold Tremblay, Edward Loller, Tom Foley, and Harold Doerfel, Aeronautical Computer Laboratory, U.S. Naval Air Development Center, Dr. Robert Laidlaw, Mr. Charles Walli, Dr. Edward Marlowe, and Mr. Jack Willer, North American Aviation, Inc., and the pilots, Lt. James Willis, USN, Lt. Paul Weitz, USN, Lt. Charles Caricofe, USN, Lt. Paul Easton, USN, Lt. j.g. C. Garber, USN, Lt. David Glunt, USN, Capt. Robert Solliday, USMC, Lcdr. William Murphy, USN, Robert Smyth, Richard Wenzell, and Donovan Heinle.

## Acceleration Terminology

In the first papers I know in which accelerations were measured in flight[76,77] a distinction was made between the accelerometer readings, called "accelerometer ratios", and the changes of velocity, which I call the displacement accelerations. In straight and level flight at constant speed, an accelerometer mass is deflected an amount which may be called 1G due to the gravitational attraction, but the displacement acceleration is zero. At other flight path angles as well, the gravitational components must be subtracted to determine the displacement accelerations. Unfortunately in the early United States papers measuring accelerations in flight[61-63,71,93] this distinction between gravitational attraction and displacement acceleration was not made, with the consequence that today it is the unusual rocket engineer who is quickly certain when you tell him that you have a 2g liftoff whether the velocity change is 32 or 64 feet/second$^2$.

In rocket vehicles, the crew are no longer necessarily in the typical airplane transverse seated position. Accelerations are no longer primarily along the transverse (Z) axis. Rotations may be more severe than with aircraft, and should be specified with more convenience than, for example, "2.0 radians per second squared about the Z axis". A physiological acceleration terminology[25] has therefore been established with recommendations for its adoption in the United States[119] and inclusion in a Table of Equivalents of Acceleration Terminologies[37] recommended for international use. This terminology has the following key points:

1. The unit for the physiological acceleration shall be G to distinguish this acceleration from the "true" displacement acceleration, generally designated by aerodynamicists with the unit g. The physiological acceleration represents the total reactive force divided by the body mass, and hence includes both displacement and resisted gravitational acceleration effects. Note that the physiological acceleration or total reactive load acceleration G rather than the displacement acceleration g is what is measured by accelerometers.

2. The physiological acceleration axes represent directions of the reactive displacements of organs and tissues with respect to the skeleton. The Z axis is down the spine, with $+G_z$ (unit vector) designations for accelerations causing the heart, etc., to displace downward (caudally). The X axis is front to back, with $+G_x$ designations for accelerations causing the heart to be displaced back toward the spine (dorsally). The Y axis is right to left, with $+G_y$ designations for accelerations causing the heart to be displaced to the left. For accelerations in which effects on the entire body are of concern, the origin of the axes

shall be half way between the anterior (rostral) surfaces of the iliac crests, with the Z axis passing through the midpoint between the suprasternal notch and the dorsal surface of the dorsal spine of the last cervical vertebra to this origin. The X and Y axes are mutually perpendicular to this Z axis.

For acceleration effects on the vestibular apparatus, the origin of the head axes shall be the midpoint between the external auditory meatuses (on the Y axis), with the X axis passing from the ventral medial margin of the nasal bones through this origin.

3. Angular accelerations which cause the heart to rotate (roll) to the left within the skeleton shall be specified by the $\dot{R}_x$ unit vector, representing radians/sec$^2$ about the X axis. Angular velocities in the same sense shall be specified by the $+R_x$ unit vector, representing radians/sec about the X axis. Similarly, $+\dot{R}_y$ represents pitch down of the heart within the skeleton, and $+\dot{R}_z$ represents yaw right of the heart within the skeleton.

4. Linear acceleration environments may be represented by the three acceleration components (along the $G_x$, $G_y$ and $G_z$ unit vectors) or by a resultant acceleration and the azimuth and altitude angles of the resultant with respect to the body axes. Azimuth is measured from the +X axis (to the back), with positive rotation clockwise as seen from above. Attitude is measured from the horizontal (XY) plane, with positive angles when in the hemisphere of the +Z axis (downward). Thus a man reclining in a chair tipped back 45° is experiencing 0.7 $G_x$ and 0.7 $G_z$, or 1G/0°, 45°.

5. Whenever rotations accompany linear accelerations, the reference point for the linear accelerations should be specified, and the time histories of the angular velocities and angular accelerations should accompany the time histories of the linear accelerations, to allow the computation of linear accelerations at other points. (Note: For complex motions, measurements vs. time of these 9 parameters ($G_x$, $G_y$, $G_z$, $R_x$, $R_y$, $R_z$, $\dot{R}_x$, $\dot{R}_y$, and $\dot{R}_z$) should be made. With improvements of instrumentation and the specifying of initial conditions, angular velocities may be adequately determined by the integration of angular accelerations, reducing the required channels to six, which may indeed be three pairs of linear accelerometers, with the accelerometers of each pair separated by a known distance. For the specification of vehicle flight paths and the determination of the displacement accelerations, the three Euler angles must also be determined, generally by integration of rate gyro signals.)

This physiological acceleration terminology is illustrated in figure 1. Figure 2 provides a comparison to the NASA vehicle acceleration terminology. It is suggested that the hybrid "normal load" terminology be dropped, to avoid the confusion possible, for example, when stating that a flight vehicle at constant velocity has a normal load of 1g. Let us restrict g to displacement acceleration, so that a vehicle at constant velocity is experiencing 0g. The crew then, if positioned transverse to the vehicle, would experience 1$G_x$ if the vehicle is climbing vertically or 1$G_z$ if the vehicle is flying horizontally, and these would be the values read by accelerometers. An alternate name for the "physiological acceleration" G might be the "total reactive load," but the former term emphasizes that the pilot body axes are used, whatever his orientation to the vehicle.

It is necessary to here extend this terminology for the jostle acceleration situation. For aperiodic jostle motions of moderate duration, time histories of the nine linear accelerations, angular velocities, and angular accelerations should be given. Until more is known, allowing the use of body motion mathematical models,[42,67] empirical experience in the actual or simulated environment will be required to determine tolerance and control capabilities, if this environment is more severe than previously studied environments. For "stationary random" jostle motions, due for example to turbulence, six linear acceleration and angular acceleration power spectra, versus frequency, may in addition to the time histories be specified, summarized by "root mean squared" or RMS values. Note that the RMS values alone are not sufficient specification of the jostle; these must be accompanied by the power spectral frequency distributions. For vehicle responses and forcing functions of moderately similar frequency distributions, with acceleration power spectra peaks between 1 and 10 cycles per second, initial comparisons of the severity of jostle may be made on the basis of RMS values alone, but power spectra should be compared before final decisions of tolerability are made.

To emphasize the displacement aspects of the jostle environment, it is appropriate to represent the jostle by an RMS g, with the understanding that this is superimposed on a specified G, with a varying degree of transmission and phase shift into specific organs of the body, as represented by the mathematical models.

## An Historical Review of Flight Simulation

The origins of flight simulation are obscure. Indeed, one of our anthropoid ancestors perhaps a million years ago probably ran about with his arms out - or jumped from a tree - and grunted, "Look, ma, I'm flying." The first pilots, having built their planes, sat in the seats and moved the controls, thinking through their flights - the beginning of "fixed base" or "static" flight simulation - then, as Stewart [81] puts it, "Men who had never been in the air in their lives before took their seat in the cockpit and opened the engine and took off to find out in a few desperate minutes whether they could fly or not." The Wright brothers (1903), J. C. Ellehamer (1906), Albert Santos-Dumont (1906), Charles Voisin (1907), Horatio Phillips (1907), Louis Blériot (1907), Robert Esnault-Pelterie (1907), Henri Farman (1907), L. Delagrange (1908), A. V. Roe (1908), Glenn Curtiss (1908), Samuel Cody (1908), Glenn Martin (1909) and others learned their flying in this way. In 1908, the first airplane flight with a passenger [40] was made by Wilbur Wright and Charles Furnas (May 14), and in 1908 the first airplane fatality[40] occurred during a training flight, with Orville Wright being seriously injured

and Lt. Thomas Selfridge killed (September 17). It is interesting to note that in April, 1962, we have yet to see our first two man rocket flight, now planned by the United States with the Gemini spacecraft and Titan launch vehicle for 1964.

In the summer of 1913, Adolphe Pégoud persuaded his employer, Louis Blériot, to allow him to attempt the first intentional upside-down airplane flight. He prepared by strengthening the airplane wings and tail, developing shoulder straps as an addition to the available lap belt, and trained by inverting the airplane on trestles and practicing operating the controls while experiencing the $-1G_z$, an early flight simulation with acceleration effects added. On September 1, 1913, Pégoud successfully flew upside down,[2,40,81] and subsequently (September 21) made full loops,[40] shortly after Nesterov looped in Kiev (August 20) an event much less widely known at the time. As Védrines said about Pégoud, "He taught the world how to fly" with his demonstrations of the maneuverability of aircraft.[81] We have yet to see the intentional looping of a rocket vehicle, that is, the demonstration of its full maneuver and emergency recovery capabilities, although I understand that an unmanned Atlas vehicle looped during thrust during an early development flight. This is quite analagous to the accidental inverted flight of H.B. Reynolds[48] in 1911 and of Pégoud's abandonned airplane following his parachute jump, which caused Pégoud to reason that with training, inverted flight could be treated as a recoverable rather than a "bailout" emergency flight condition. In the same way I look forward to the first intentional looping with thrust - not just tumbling with attitude control, although this should occur first - of the X-15 or Mercury or Gemini or Dyna-Soar, to break the bonds of viewpoint which still bind manned rocket flight to the precise dull mathematical non-adaptive essentially ballistic launch flight paths, and show that manned maneuvering rocket flight "design path" deviations are not a cause for aborting the flight.

In 1918, recognizing that many crashes were due to vestibular disorientation leading to "ear deaths"[52], the Ruggles Orienter was developed[3] to tumble pilots in all three rotational axes and introduce them to the range of their vestibular sensations, the anticedent of the "Multi-Axis Spin Test Inertia Facility" used to tumble the Mercury astronauts at rates up to 50 revolutions per minute about all three rotation axes and train them in the use of the Mercury attitude control equipment.[83] The Ruggles Orienter, with a covered cockpit, was used by William C. Ocker in early simulations of blind flight using the Sperry turn indicator, developed in 1917.[52] For more extensive field use, David Myers and William Ocker utilized the "turning chair with the instrument box", (fig.3), a Barany chair and a turn indicator, to train pilots in the distinction between their subjective feelings of rotation and their actual rotations.[52] The development of the Link trainer in the mid 1930's gave pilots a quite detailed "closed loop" pilot control moving base (or "dynamic") simulator, in which pilot control continuously modified cockpit instrument readings and simulator angular motions, limited in range in roll and pitch. In this same period, the first of the power driven human centrifuges were built[25], but their initial use was to provide pre-programmed rather than pilot controlled flight simulation accelerations. Further refinements in simulated vehicle characteristics awaited the development of the electronic computers following World War II.

The rocket flight pioneers, from Sanders (1928), von Opel (1929), and Warsitz (1939) to Milburn Apt (1956), who was killed in his first flight in the X-2 after reaching 2078 miles per hour, and indeed the rest of the proud line of test pilots in any new airplane up to this period, made their first flights in vehicles which could have quite different characteristics from any they had previously experienced. It was in this mid-1950 period that flight simulation began to catch up with the complexities of actual flight, so that now our X-15 pilots, our Mercury pilots, and apparently our Vostok pilots are intimately familiar with the handling qualities and flight loads of their vehicles under normal and emergency conditions before their first flights. Thus Robert White,[89] after his X-15 flight to 217,000 feet, stated[89], "...the static simulations and the Johnsville centrifuge program contributed to very good training for these conditions so that the actual reentry did not result in a completely new or unexpected flight experience." Other moving base or dynamic flight simulators for the X-15 included a T-33 variable stability aircraft [7] and, of particular use, an F-104 landed with dive brakes extended to simulate the lift-drag characteristics of the X-15[30]

With the development of electronic analog computers after World War II, both computations of aircraft performance and the use of airborne electronic components to change control responses and improve auto-pilots were greatly expanded. An historic moving base, pilot controlled flight simulator of this period was the NACA Langley Aeronautical Laboratory "elevator seat", developed by William H. Phillips,[69,89] using an hydraulic analog of an aircraft response to control a seat moving vertically on rails in response to pilot control stick motions. By the mid-1950's, electronic control of aircraft responses was such that one airplane could have its responses modified to feel like another airplane, and the variable stability airplane was created, particularly by work at the NACA Ames Aeronautical Laboratory (for example, reference 58) and the Cornell Aeronautical Laboratory (for example, ref.55)

In 1948, William Phillips[68] had theoretically predicted the decreasing stability problem of short wing aircraft at higher speeds which came to be called the "roll coupling" problem. This and other stability problems associated with thrust misalignment and limited control effectiveness at high altitude were being faced by the rocket airplane pilots. Charles Yaeger vividly described[92] a flight on December 12, 1953: "You reach a maximum speed of 1650 miles an hour - twice the speed of sound! Your fuel exhausted then, you pull out through the same violent buffeting and shock into the transonic range again. Then suddenly you lose control of the ship....Your mind is half blank, your body suddenly useless, as the X-1A begins to tumble through the sky. There is something terrible about the helplessness with which you fall.

There's nothing to hold to and you have no strength. There is only your weight, knocked one way and another as the plane drops tumbling through the air. The whole inner lining of its pressurized cockpit is shattered as you're knocked around, and its skin where you touch is still scorching hot." Elsewhere[91], he added, "The airplane finally pulled about 11g's upward," (that is, $11G_z$)," tried to stabilize itself, and of course then started snapping and I was pretty well blacked out due to the high acceleration forces." The pilots were beginning to have flight experiences for which their previous training was inadequate.

The F-100 was the first production aircraft in which severe roll coupling was a problem, although the F-86 had a "pitch-up" characteristic under certain flight conditions[30]. First flown in May, 1953, the F-100 had already "become uncorked" and killed test pilot George Welch when in late 1954 it came to the NACA Flight Test Center, where the roll coupling problem was evaluated in flight[30].

At about the same time, a fixed base pilot controlled display simulator, with five degrees of freedom electronic analog flight mechanics computation was developed to seek solutions for the F-100 inertial coupling problem, under the direction of Leonard Sternfield at the NACA Langley Aeronautical Laboratory[80]. This simulator represented major refinements over the airplane procedures trainers of World War II in utilizing far more detailed computations of flight performance. Today we have many fixed base pilot controlled display flight simulators or procedures trainers, with electronic analog computation of detailed flight response and display changes as a consequence of pilot control motions. Many more "flights" can be made in the simulator than in the actual vehicle. Hazardous boundaries can be explored both from the safe and from the unsafe sides, to establish cockpit design, pilot technique, and training before confirmation of the data in actual flight. As a result of simulator and flight studies, a larger tail was put on the F-100, to reduce the inertial coupling problem.

Sir George Cayley had written in 1846 about the remaining problems of flight[40], "A hundred necks have to be broken before all the sources of accident can be ascertained and guarded against." Now pilot control simulation had reached a precision such that many sources of accidents could be identified and eliminated before the first flights. But the consequences of pilot motion could still not be adequately predicted. In the early 1950's, an autopilot was under development by the Bell Laboratories to allow automatic tail-chase tracking. This would subject the pilots to considerable jostle during which they might have to take over flight control. In 1952 the Navy Johnsville human centrifuge was dedicated. This centrifuge (figure 4) has a double gimbal system at the end of a 50 foot centrifuge arm, allowing three degrees of freedom of motion control. The first moving base flight simulation utilizing this gimballed centrifuge capability[34] determined that pilots experiencing the pre-programmed computed motion could tolerate the automatic interceptor control mode. Subsequently, computer refinements of the interceptor system were made[75], partly with the use of the U.S. Naval Air Development Center "Typhoon" analog computer, which had been developed in cooperation with the Moore School of the University of Pennsylvania.

On September 27, 1956, Milburn Apt was killed during his first flight of the X-2 rocket airplane, when he initiated a turn at too high a speed, and lost control[32]. He had not previously trained in this type of motion environment. In 1956, North American Aviation Inc. representatives, who had been awarded the development contract for the X-15 research airplane, approached the Navy to use the Johnsville centrifuge to determine the consequences of accelerations simulating those computed for the X-15 under certain extreme flight conditions (figure 5) on pilot control capabilities[16]. The first study, carried out in March, 1957[27,53], used pre-programmed cam control of the centrifuge. Pilot tolerance to the expected accelerations was confirmed, and aspects of cockpit design were studied. Fig. 5 shows one of the cam control runs.

But the consequences of pilot motion on vehicle control modifying subsequent motion and control could not be studied by pre-programmed centrifuge operation. A project was therefore initiated by John L. Brown and the author to control the centrifuge through the Typhoon analog computer, such that as the pilot moved his flight controls, the computer would continuously determine the changes of flight path, provide signals to the cockpit display instruments to show the changing flight conditions (as with the usual fixed base simulator), and at the same time provide drive signals to the centrifuge so that the pilot experienced the accelerations that he would have experienced if he had made the same control motions in actual flight.

With the active participation of the Aeronautical Computer Laboratory staff of the U.S. Naval Air Development Center, and of representatives from the Moore School, University of Pennsylvania, the first moving base pilot controlled motion and display flight simulation, with three degrees of freedom of centrifuge motion, was carried out in July, 1957[17,69]. With the encouragement and participation of NACA, particularly of Leonard Sternfield and his stability and control group of the Langley Aeronautical Laboratory, this new technique was applied to two further studies of the X-15[27,90,19] with extensive participation by representatives of North American Aviation, Inc., in the final study. Over 600 centrifuge moving base flight simulations of the X-15 (and tens of thousands of fixed base simulations with the North American Aviation simulator) were made before the first actual flight. Fig. 6 shows one of the pilot-computer control runs.

With three X-15 aircraft, and over 50 flights, with altitude and speed advances made in small increments, centrifuge training at the beginning of the program, rather than on a flight by flight basis, has been adequate. With experienced pilots, with training maintained by periodic actual flights, detailed flight planning is adequately done using only the fixed base simulator. With vehicles going into orbit and beyond, initially one man will make less frequent flights. In this early "sling shot era"[23] of rocket travel in which most of the thrust is delivered in the first few minutes of

travel, design and emergency accelerations are high enough that training in the straining procedures [20], and in continuing control and display monitoring in spite of discomfort, should be maintained.

Over 1000 Navy centrifuge moving base flight simulations[18,83] of NASA project Mercury were carried out before the first flight, but it is not yet established what frequencies of the various moving base simulations should be used to maintain astronaut proficiency in this early period in which actual flights by a particular astronaut will be many months apart. Indeed, the actual flights will hopefully never involve the extreme emergency accelerations, for which training should also be maintained. Moving base flight simulation should remain a periodic task of this pioneering rocket era so that the astronauts, like their successful brothers of the pioneering airplane era, can step into their vehicles and fly them correctly the first time, and each time.

It is emphasized that the centrifuge cannot provide a perfect motion simulation of a flight vehicle, nor can any simulator which does not precisely follow the flight path of the vehicle of concern. Unconstrained flight, with six degrees of freedom of motion, may be analysed in terms of three linear acceleration and three angular acceleration time histories which must be matched for perfect motion flight simulation. The Johnsville centrifuge has independent controls for arm angular velocity (limited to 0 to 3.6 rad./sec., giving 20G, when the gimbals are used) and the inner (usually limited to +85° to -85°) and outer (limited to 0° to 90°) gimbal angle positions.

These limited range, three degrees of freedom of motion may be controlled to simulate the three linear accelerations (see for example figures 5 and 6) but at the expense of incorrect angular accelerations, although the position of the pilot can be regulated to at least provide critical angular accelerations in the same sense if not the same magnitude in comparing flight to centrifuge simulation [10]. Vehicle aerodynamics affects the simulation precision; with an approximate simulation of the linear accelerations, angular motions of the gondola exceeded those computed for the X-15 but were less than those computed for the Mercury vehicle.

For any moving base simulator, the importance of these "motion artifacts", or inaccurately simulated motions, must be judged, ideally by a growing body of "flight validation" experience [11, 89,78,45,41]. Under certain circumstances the artifact motion cues may provide an incorrect training experience or produce an artifact performance effect, leading to incorrect conclusions made on the basis of simulator experience alone. In the future, this validation experience should be used to establish psychophysiological equations representing reactions to motions. Computations of the six degrees of freedom accelerations of the flight vehicle can then be modified by these psychophysiological equations in controlling the limited degrees of freedom of the simulator, in order to minimize these artifact motion reactions and consequent artifact performance effects. This may involve a continuous change from linear acceleration to angular position or angular acceleration control, in order to provide the simulation which feels the most realistic within the capabilities of that simulator.

For certain aspects of training it may not be required to provide a precise simulation of the accelerations, so long as the simulated experience feels like - or the evoked performance is like or more than adequate for - the real flight experience. Thus after obtaining initial tolerance experience, repeated training for emergency conditions might be carried out for the most part at less than the emergency accelerations. Jostle control capabilities may be judged as adequate following demonstration of capabilities in a more severe albeit not precisely simulating jostle environment. It is just this capacity of the human to evaluate present experience in terms of remembered more stressful past experience that allows the greatest part of the training to be made on fixed base or very limited motion flight simulators. But the frequency that the moving base simulator or actual flight vehicle must be used in order to retain this "transfer" experience has not yet been evaluated.

The refinements and use in combination of other aspects of simulation, including low pressure[21], gas composition, temperature[14], noise, out-the-window visual appearance[13], prerun rest, food, and flight preparation activities, etc. must all be added to the cockpit configuration, control and display actions, and motions to minimize performance artifact due to simulator training. How soon will we be able to awaken an astronaut, transport him to a device, and "launch" him with such fidelity that he is unable to tell whether he is in real or simulated flight? With the costs of one manned rocket flight in this early period probably more than the costs of all pilot control simulation studies to date, simulation improvements which even slightly reduce the probability of real accidents are justified.

Moreover, now that we are developing refined simulation techniques, all future "environmental pioneering" [20] or the first entering by man of predicted new environments, should first be made in simulation so that consequences can be evaluated with help at hand. Many more people should study the effects of new environments in simulation than in an early period meet them in reality. Thus our "simulo-astronauts" [20], who only "go boom in black boxes" rather than in real flight, have a part to play in present day space pioneering. Today there are five people who have made five actual flights above 100 miles altitude; there are perhaps 50 people who have made perhaps 2000 "flights" in moving base simulators to a simulated orbital condition.

It is emphasized that this is a preliminary historical review of flight simulation, particularly of moving base flight simulation. The extensive development of pilot-computer controlled procedures trainers, and the increasing addition to these of at least some minimum cockpit motion, warrants a thorough documentation. Figure 7 diagrams the motion capabilities of a number of types of moving base simulation facilities. Reports of the Acceleration Panel[38,46,85] of the Armed Forces - National Research Council Committee on Bioastronautics, and of the informal international Acceleration Group continued under the

Chairmanship of Dr. James D. Hardy after the disbanding of the Committee on Bioastronautics, with one meeting[50] under the sponsorship of the National Academy of Science Space Science Board Man in Space Committee and the National Aeronautics and Space Administration, and with additional meetings under consideration, provide details about these facilities and programs.

In conclusion of this preliminary review it is suggested that at least the following aspects of a flight simulation should be specified when referring to it:

a) Identify the simulator used.

b) Is it a "fixed base" (stationary cockpit) or "moving base" (moving cockpit or pilot control area) simulation? The terms static or dynamic simulation should be dropped because of confusion by some as to whether these latter terms refer to the cockpit or display motions.

c) If it is a moving base simulation, give the number of degrees of freedom or independent control parameters of the motion.

d) Does it have pilot control? Does the pilot control (through the vehicle response equations) both the cockpit motion and the display changes, or does he ride a pre-programmed motion and control only the display? The previously used terms of closed loop and open loop simulation for these conditions should be dropped because of the confusion by some people, since in both cases display changes are in a closed loop relation to pilot control actions.

e) Give the number of degrees of freedom of the flight mechanics computation.

f) State additional aspects of the simulation, such as noise, low pressure, temperature effects, out-the-window display, pre-flight activities, etc.

Consider two examples: 1) The Martin-Baltimore fixed base pilot controlled display lunar landing simulator, with five degrees of freedom of flight mechanics computation, and 2) the Navy Johnsville centrifuge moving base three degrees of freedom of motion pilot controlled motion and display Mercury simulator, with six degrees of freedom of flight mechanics computation, and with pre-launch diet, rest, and preparation, flight noise, low pressure, and gas composition simulation.

## Vibration Studies

No attempt will be made here to review the vibration literature[42,74], nor give the characteristics of vibration devices[85]. Early work with low amplitude (less than 1g RMS), moderate frequency (5-20 cps) devices with sine waveform vibrators is now being extended by devices capable of higher accelerations at lower frequences, having greater amplitudes of motion, and in some cases having complex waveform control systems. Vibration programs are particularly noted at the Naval Medical Research Institute, Bethesda[42]; the Aerospace Medical Laboratories, Dayton[42,94,73]; the Army Medical Research Laboratory, Fort Knox[74,72]; the Bostrom Research Laboratories, Milwaukee[51]; the Boeing Company, Wichita[65,66]; the Grumman Aircraft Engineering Co., Bethpage[54]; the Bell Helicopter Co., Fort Worth[50]; the U. S. Army Ordnance Tank Automotive Command, Detroit[70]; Ohio State University, Columbus[36]; and the RAF Institute of Aviation Medicine, Farnborough, England[47]; in addition to work at the U. S. Naval Air Development Center, Johnsville[59,88]; and the North American Aviation, Inc., Columbus[5], further described here. Russian[64,84,79], German[33], French[43] and Japanese[64] studies are noted.

Previous work has dealt primarily with effects of steady sine wave vibrations. For such vibrations of elastic (and biological) structures near resonance frequencies, large resonance amplitudes of the elastic structures can be built up for small amplitudes of the forcing structure. With "complex waveform" excitation, much of the vibrational energy will be at frequencies other than those of resonance, resulting in a lower amplitude of the elastic structure than if all of the energy were at a resonance frequency. On the other hand with complex waveform excitation, partial resonances of adjacent structures at different frequencies can occur simultaneously. With the expected non-linearities of biological interactions, excitation with complex waveform giving multiple resonances might produce more damage than sine wave excitation. In addition, with complex waveform excitation, individual acceleration peaks show a variation from the steady sine wave amplitude from much larger to much smaller, with the former possibly producing more damage.

Previous work with sine wave vibrations in the 1 to 10 cps region had indicated a considerable spread in peak accelerations which subjects refuse to tolerate, from about a 0.3 $g_z$ peak[42] (or 0.2$g_z$RMS) for 5 to 20 minute exposures with moderate motivation to about a 2$g_z$ peak[94] (1.4$g_z$RMS) in the frequency range of 4 to 8 cps for a few seconds exposure with greater motivation. Parks and Synder[66] report the "alarming" level of sine waveform vibrations as 0.4 to 0.9G (0.3 to 0.6$g_z$ RMS) at 1 cps, and 0.3 to 1.05G (0.2 to 0.7$g_z$ RMS) at 5 cps, for different subjects. On the other hand, single acceleration events of even 10$G_z$ and higher at a frequency of 1 cps or higher are quite tolerable. How often could these larger amplitude events be repeated in a given time for the motion still to be acceptable, if they occurred with a complex waveform, hence with periods of rest between the high acceleration events? With the general increase in blood pressure and pulse rate following a moderate acceleration event, tolerance to a later acceleration event might for certain conditions of time and magnitude be increased by previous exposure to a "conditioning" acceleration event.

Vibration can produce damage. Riopelle et al[72] had one monkey die in one hour and two survive eight hours of 10 cps, 0.25 inches double amplitude sinusoidal motion, or 0.9 $g_z$ RMS. At 0.5 inches double amplitude, one monkey died after 7 hours of vibration, one died the next day, and two survived 8 hours of vibration (1.8 $g_z$RMS measured at the seat). Severe chest pain[88] has developed in some humans after 25 seconds of sine waveform vibration at a double amplitude of about 0.15 inches in the frequency range of 10 cps (about 0.5 $g_z$RMS) and

and White himself[88], after 15 minutes without pain at 20-25 cps with a double amplitude of 0.17 inches (about 2.4 $g_z$RMS) later observed blood in the soft stools. Medical monitoring is recommended for environmental pioneering studies. It is emphasized that "tolerable" and "damaging" levels of vibration will vary depending on the nature of the body support-restraint system[73].

Performance is also affected by vibration. With a sine waveform motion of frequency below 10 cps., the pilot can anticipate or brace again the uniformly repeated changes of acceleration in making his control motions. With complex waveform motion on the other hand the phases and amplitudes of successive acceleration events are not uniformly repeated, and involuntary pilot control motions would expectedly increase.

Brief studies were therefore initiated on the Johnsville centrifuge and the North American Aviation "G seat" to determine the tolerance and performance decrement effects of the severe complex waveform vibrations of concern.

A "Chronological Bibliography on the Biological Effects of Vibration", by Carl Clark and Keith McCloskey[26], *similar* in format to the "Chronological Bibliography on the Biological Effects of Impact"[22,59] is in preparation.

## Jostle with the Navy Johnsville Centrifuge

Centrifuge jostle is obtained by varying arm and gimbal angular velocities, using a "white noise" electrical source shaped electronically to give the desired $G_z$ power spectrum. These variations must be precisely controlled[28] in amplitude and phase in order to simulate particular time histories of the three linear accelerations. The simulation may be described as follows: moving base Navy centrifuge jostle simulation, with three degrees of freedom of preprogrammed jostle motion and pilot controlled maneuver motion, with pilot controlled display and three degrees of freedom of flight mechanics computation.

As shown in figures 5 and 6, it is difficult to eliminate the $G_x$ acceleration artifacts. For large and rapidly varying linear accelerations, the angular motions of the centrifuge gondola are also large, as illustrated in figures 8, 9, and 10, for a $5G_z$ haversine waveform of 10 second period. These angular motion artifacts can be nauseating, producing performance artifacts. The centrifuge is most useful for simulating flight accelerations above perhaps 3G, for variations at higher accelerations require smaller gimbal motions.

On the other hand, flight jostle generally involves angular as well as linear motions. Jostle with the three degrees of freedom of control of the centrifuge does indicate some of the restraint and control problems which might not be apparent on a vertical accelerator with only one degree of freedom of motion. If low amplitude jostle is considered acceptable on the centrifuge, it would probably also be acceptable in the less severe actual flight conditions.

Although $-G_z$ accelerations can be provided on the centrifuge by tipping the subject's head "outboard", rapid oscillations from $+G_z$ to $-G_z$, passing smoothly through 0G, can only be provided at points away from the center of the gondola, using rapid gondola rotations out from under the subject to give brief moments of true 0G or $-G_z$. The potential of this technique is illustrated in the bottom tracing of figure 11. Although the centrifuge arm begins to have amplitude loss near 1 cps., the gimbals can follow motions to about 5 cps.

Under usual conditions, when the computer commands a resultant acceleration of less than 1G, the centrifuge simply stops. In order to avoid this continual starting and stopping, a "bias acceleration" of 2 or 2.5G was utilized, a technique first suggested for use at the Johnsville centrifuge by the NASA Ames group (B. Creer, M. Sedoff, G. Rathert, R. Wingrove, et al.). Hence with a jostle or pilot maneuver input, the centrifuge would speed or slow about the 2G level. This provides acceptable simulation of low amplitude jostle, but at higher amplitudes the very important non-linear effects of lifting out of the restraint system when passing through 0G are not provided on the centrifuge except with the offset seat position[79]. A vertical accelerator provides a better simulation of flight jostle than the present Johnsville centrifuge.

A brief examination of tolerance to acceleration events repeated within seconds was made. Three subjects were used. One blacked out with a $4.2G_z$ haversine of 30 second period and the other two greyed out at a $4.0G_z$ peak. The first again experienced blackout with the first cycle of a $4.0G_z$ haversine of 15 seconds period but had clear vision for the second cycle. The other two, with dimmed vision on the first cycle, had clearer vision on the second. There is a conditioning effect of an acceleration event.

With a $4.0G_z$ haversine of 10 seconds period, the first subject had a visual dimming on the first and third cycles; a fatigue or decompensation effect may be setting in. The second subject had a dimming on the first cycle, but clear vision on the next two cycles. With a $4.8G_z$ haversine of 5 seconds period, the first subject had no visual dimming for 6 cycles, and the second subject had a similar experience with $4.5G_z$ peaks.

Centrifuge response capabilities limited study with higher haversine peaks of shorter periods, although the Johnsville centrifuge has been used to show human tolerance to a single $15G_z$ "spike" of 1.75 seconds width[4], with the gimbals prepositioned.

A curve showing RMS g tolerance versus frequency would therefore rise from the 2G peak for 24 hours point[24] toward the $4G_z$ peak blackout level to some higher $G_z$ value for repeated acceleration spikes near about 1 cps (with the maximum tolerance expectedly - on a teleological basis - in the 0.5 to 1 cps range of walking) then falling again as the torso resonance frequency (4-8 cps) is approached, then rising again at higher frequencies of the seat motion. As specific points, the first subject, discussed about, experienced a $2.5G_z$ peak haversine waveform ($1.2g_z$RMS oscillating about $1.75G_z$) of 3 second period for 5 minutes with only moderate post-run nausea, and the second subject experienced a 1.6 $G_z$ peak haversine waveform (0.2$g_z$ RMS

oscillating about $1.3G_z$) of 2 second period for 5 minutes with only slight post-run nausea.

It is interesting to note that head motions in these multiple rotation jostle environments did not seem from brief observation to be as disorienting as head motions in a steady rotation situation. In the latter case[24], for a body rotation of 10 rad/sec (2G centrifugation) head motions such that the vector product of the head angular velocity and the body angular velocity exceeded 0.06 $rad^2/sec^2$ were discernible as a Coreolis illusion[44], and (in brief observations with one subject) if the vector product exceeded 0.6 $rad^2/sec^2$ nausea developed. In the jostle situation, perhaps the short duration of any particular rotation rate or perhaps the lack of distinguishability of a rotation illusion from an actual rotation a moment later seems to suppress the nausea level, although eventually centrifuge jostle becomes nauseating.

Jostle with the North American Aviation "G-Seat"

A moving base simulation of flight jostle was carried out in June, 1960, with the North American Aviation, Inc. "G-seat" (figure 12) with one degree of freedom (vertical acceleration) of preprogrammed jostle motion, pilot controlled maneuver motion in $G_z$, and pilot controlled display (roll and pitch changes), with three degrees of freedom of flight mechanics computation. Fig. 13 shows the frequency response capabilities of the G-seat, and Fig. 14 shows the power spectrum[31, 56] of the jostle motion of concern. The power spectral density ordinate of this figure is given in units of $sec^{-1}$, representing density in units of $g^2$ per cps normalized by the square of the RMS jostle, in g units, times a constant with the value of 20 sec. Dimensionally:

$$\frac{\Phi}{(K g_{RMS})^2} \qquad \frac{g^2\ sec}{(cycles)\ sec^2 g^2} = sec^{-1}$$

In actual flight[57], jostle level (represented by an RMS g level, and also possibly a changing power spectrum shape) will vary with time[31]. Indeed, if this change is too rapid (less than perhaps 20 sec. of fairly consistent jostle) the power spectrum description of jostle is not adequate, for this description assumes a "stationary random" process independent of phase relationship. In such cases, it is urged that the entire time histories (ideally of three linear accelerations, three angular accelerations, and three angular velocities) be given. Moreover, until the power spectrum description is more familiar to biologists, representative actual acceleration time histories should be presented even in cases in which the power spectrum description is adequate.

There are cases in flight in which the complex wave form jostle is not a "stationary random" process, with continuously ("randomly") varying amplitudes and phase relationships of the different frequency components, but is a true periodic complex waveform. It then has constant phase relationship and amplitudes of the different frequency components, suitably represented by a Fourier analysis of these amplitudes and phase relationships, often with narrow band resonances of particular vehicle structures clearly distinguishable.

As at Johnsville, the jostle command signal was generated by shaping a "white noise" electric source with a filter of proper transfer function. In addition, the pilot operated a usual center control stick in pitch and roll, with pitch commands affecting through the vehicle response equations both the G-seat motion and display changes, and roll commands affecting only the display.

Because of the limited travel of the G seat ($\pm$ 5 feet for regular use), maneuver loads would initially be felt, but would be rapidly "washed out," with the G seat having a bias drift back to the center position. This can be seen in the lower part of Figure 15, in which the command channel shows maneuver loads, but the response channel does not. Indeed with large maneuver load commands it was possible to briefly bump the G-seat against its top or bottom limits, as shown in Figure 15.

The RMS $g_z$ values used in this report are the expected response values. Unfortunately, equipment was not available to determine the actual RMS accelerations. The measured seat acceleration time histories are however quite reasonable for these expected response values, with peaks of 4 times the RMS g value every few seconds for example. The panel accelerometer values are means of many readings which, of course, represent maximum seat response maneuver plus jostle loads during an entire run. These maximum values may not be observed during a particular brief time period of an accelerometer recording (for example, Figures 15 and 16).

The pilot wore a Navy torso restraint system, with attachments at the shoulders and sides of the hips. His primary display was a five inch face oscilloscope. His task was to follow a command line moving in response to three sine waves with 44, 19, and 13 second periods with relative amplitudes of 6 to 4 to 2. Pilot anticipation of the task requirements were provided by two additional scope lines, of decreasing length, which indicated the task positions one and two seconds later. Vehicle roll was indicated by another line on the scope. The task was to track in pitch and hold roll 0, correcting for any involuntary or unintended inputs in roll.

A green light above the panel oscilloscope was on if the tracking error was less than a relative amplitude of 1 (i.e. 1/12th of the task range); the time this light was on during a typical 100 seconds of jostle was recorded. A red light came on if the tracking error exceeded about a relative amplitude of 10, i.e. 5/6 of the task range; the number of these events were counted. See the classified reports for further details of these tasks.

The pilots tracked without motion, then with maneuver loads only, then with increasing levels of jostle of 0.15, 0.35, 0.50, and 0.70 $g_z$ RMS. Subsequent exposures with the same subject did not repeat this entire set. Fourteen subjects made 70 moving base runs; this can only be considered as a preliminary study. Three runs were of longer duration: 0.35$g_z$ RMS for 15 minutes, 0.50$g_z$ RMS for 5 minutes, and 0.35$g_z$ RMS for 30 minutes (Solliday).

## Complex Waveform Jostle Tolerance

For the acceleration power spectrum used (Figure 14), the jostle was not uncomfortable until the spinal axis load went below $0G_z$, and the pilots began to lift out of their seats. Table I summarizes the jostle levels used, and

Table 1: Jostle Conditions

| Computed Jostle Accelerations | Measured Cockpit G Meter | Pilot Comment | Tolerance |
|---|---|---|---|
| 0 | 0 to $2G_z$ | Maneuver loads only. | A pleasure. |
| $0.15g_z$RMS | 0 to $2.5G_z$ | Mild turbulence. | Not uncomfortable. |
| 0.35 | -1.2 to $4.0G_z$ | Very severe turbulence. | Fatigue limiting in 30 minutes. |
| 0.50 | -2.5 to $5.0G_z$ | Never more than one of these jolts in flight. | Not limiting in 5 minutes. |
| 0.70 | -3.0 to $5.5G_z$ | Still flying. | Not limiting in 100 seconds. |

their effects. Following $0.35g_z$RMS, the panel accelerometer with maximum and minimum needles recorded -1.2 to $4.0G_z$. The torso restraint system was inadequate, even with very tight straps, to hold the subject in his seat. The pilot would therefore begin to "splint" in place, pushing on the rudder pedals to force the shoulders against the seat back and reduce body "slap" in the restraint. To the experienced pilots the $0.15g_z$RMS level felt like flying a fighter aircraft in mild turbulence, and the $0.35g_z$RMS level felt like flying in very severe turbulence. Higher levels, except for perhaps single jolts had not been experienced by the pilots in flight.

These higher levels could however be tolerated. The $0.5g_z$RMS level, with accelerometer swings from -2.5 to $5.0G_z$, required vigorous splinting. Some subjects also forced their helmets against the seat back, to reduce head "slap" which would expose the head to far higher accelerations than the seat. Other subjects, by tipping their heads forward and with perhaps faster neck reflexes, did not attempt to lock their heads in position until the $0.7g_z$RMS level.

For these highly motivated subjects doing a tracking task which held their entire attention, "tolerance" of these jostle levels seemed essentially fatigue limited. Even the $0.70g_z$RMS level, with accelerometer swings from -3.0 to +$5.5G_z$, had as its primary discomforts the head and body "slaps" due to motion with respect to the seat and the fatigue of trying to splint or lock the body in place, not limiting in 100 seconds. One pilot tolerated the $0.50g_z$RMS level for 5 minutes and could have gone longer. Another subject tolerated $0.35g_z$RMS for 15 minutes and could have gone longer. Another subject, after 30 minutes at $0.35g_z$RMS, was glad to stop, and felt that this duration was close to his fatigue limit unless he had extreme motivation.

Two subjects experienced diarrhea during the experiment, attributed to other causes. One subject experienced a "pulling" sensation under the seventh rib on the left side from 30 minutes (delayed onset) to 5 hours after a set of jostle runs. Several subjects experienced brief headaches during their runs, attributed to helmet contact against the cockpit. The G-seat runs were neither nauseating nor disorienting (although the centrifuge jostle runs often were). Microscopic examination of the urine indicated no blood due to the jostling.

It was felt that tolerance could be extended by using an improved restraint, as has been shown[73], perhaps using inflated air bags[1,36] to allow rapid tightening of the restraint just prior to use. A foam restraint system (Figure 16) is also under development[37].

The tolerance observed in this experiment is commensurate with other experience[42,12] that above 0.3g humans are increasingly uncomfortable, with different "tolerance" values explainable perhaps in terms of differences of task complexity and motivation. Brief observation suggests that $0.3g_z$RMS of complex waveform is less comfortable than $0.3g_z$RMS of a low frequency sine waveform, because of body and head "slap" problems. A systematic comparison program would be appropriate.

## Performance

Figure 17 summaries the tracking performance of the nine pilots. They experienced the low jostle levels first; they learned to splint in place, minimize involuntary control inputs, and not be startled or unduely distracted by the jostle experience. Learning "plateaus" were probably not reached however.

The pilot with the best tracking was able to stay within the loose error tolerance even at $0.5g_z$RMS but his time within the tight error tolerance was cut from 54 to 26%. The mean scores on the other hand show, at $0.5g_z$RMS, errors beyond the loose tolerance about every 5 seconds and time within the tight tolerance cut from 32 to 13%. The pilot, experiencing accelerations in the range of -2.5 to $5.0G_z$, could not be said to be flying with precision, as he experienced considerable involuntary control input in both roll and pitch.

The display, with its four moving lines on the scope face, was not always readily interpreted by the pilots, although "double vision" due to vibration[59] did not occur. Hence during severe jostle, decision delays expectly increased (although not directly measured) and voluntary control action in the wrong direction increased. The pilots found the panel lights indicating tight and loose tolerance error helpful in making control decisions.

It would be appropriate to develop this use of lights to reduce the requirement for clear vision by the pilot. In a severe motion environment the display should be useable even if the pilot is jouncing within the cockpit. An ideal display for a previously planned flight path would provide him with indications of the optimum control for him to make to follow the desired path, with a one to one relationship, without crosstalk, of the display parameter and the particular control parameter required.

The task used was severe, requiring constant attention by the pilot. In a number of cases, questions to the pilot during jostle, or statements to him such as "The movie camera is starting now" led to his developing large flight path deviations. Questions which required repeating back numbers in the answer were answered incorrectly (at $0.35 g_z$ RMS), due to the necessary task concentration. Glances to other parts of the instrument panel or outside the simulator often preceded large flight path deviations. Pilot control during severe jostle is jeopardized, and requires his full attention.

## Control

Figure 18 shows typical pilot pitch and roll controls. At $0.35 g_z$ RMS, involuntary inputs are not obvious to the pilot. At $0.5 g_z$ RMS involuntary inputs vecome obvious. In the lower part of Figure 18, involuntary pitch and particularly roll inputs are shown accompanying acceleration peaks. For $G_z$ motions, involuntary roll control becomes especially troublesome when a jostle peak occurs during a roll input, and hence when the weight of the stick acts with a moment arm about its floor pivot. In the jostle environments particularly, abrupt control "pulses" are frequently terminated with overshoot in the opposite direction (Figure 19).

A side arm controller[15] would probably give less involuntary control input. A "digital control" (Figure 20) proposed by the author[18] could be used with even greater certainty of making definite control signals in the presence of jostle "noise". Push button operation generates a signal of precise magnitude precisely terminated without overshoot when the button is released (Figure 19). This digital or switch control is particularly useful when the pilot is providing stability augmentation, damping oscillations at 0.3 to 3 cps. Control gain is changed by a toggle switch on the controllers. One of these also has trim knobs for providing low frequency analog control.

## Comparison of the Effects of Different Jostles

It would be desirable in specifying a random jostle for biologists to give not only the RMS g level and the acceleration power spectral density but also to give a more readily recognized distribution of acceleration peak heights, in the form of the standard deviation of peak heights, and some "relative jostle biological effectiveness" frequency weighting function to allow the comparison of the biological effects of jostles with different frequency components. This "relative jostle biological effectiveness" (RJBE) weighting function is analogous in concept to the "relative biological effectiveness" concept used in high energy radiation biolcgy, and has analogous limitations that the effects with different jostle frequencies, or different radiations, may not be comparable. One must specify the effect, such as lethality, nausea, body core temperature elevation, tracking control performance, visual resolving power, etc.: the relative jostle biological effectiveness functions vs. frequency will presumably differ for these different effects. The "tolerability" RJBE function for a seated man with lap belt and shoulder straps would have the general dependence on frequency discussed in the Vibration Studies section, with a minimum at the body resonance frequency range of 4-8 cps.

For an acceleration power spectrum $\Phi_f$, vs. frequency $f$,

$$\text{RMSg} = \left[\int \Phi_f \, df\right]^{\frac{1}{2}}$$

We may then define

$$\text{biological effect RMSg} = \left[\int \Phi_f \, RJBE_f \, df\right]^{\frac{1}{2}}$$

using the appropriate relative jostle biological effectiveness frequency function for the particular effect of concern, and

$$\text{the biological effect power spectrum} = \Phi_f \, RJBE_f$$

We may also define

$$\text{total spectrum RJBE} = \int \Phi_f \, RJBE \, df \Big/ \int \Phi_f \, df$$

which experiment may show is adequately represented by

$$\text{total spectrum RJBE} = \frac{\text{RMSg at 5 cps}}{\text{RMSg of the jostle}}$$

for those RMS g values required to give the same biological effect.

Note that for two different acceleration power spectral sources, when $\int \Phi_1 \, RJBE \, df = \int \Phi_2 \, RJBE \, df$, that is when the biological RMS g's are equal, the same biological effect should be observed. Equations of this form must be adjusted to give the most suitable relative jostle biological effectiveness functions; it is expected that the use of the 5 cps sine wave as a standard may not be adequate for many biological effects.

Until further information is available, a preliminary tolerability $RJBE_f$ function might be based on one tenth of the reciprocal of the vibration tolerance for military aircraft[39, 42], extended in frequency range, hence with the following values:

Table II

| Frequency | Preliminary Relative Jostle Biological Effectiveness |
|---|---|
| 0 - 0.2 cps | 0.07 |
| 0.2 - 1.0 cps | 0.07 increasing to 1.0* |
| 1.0 to 20 cps | 1 |
| 20 - 100 cps | 1.0 decreasing to 0.07* |
| > 100 cps | 0.07 |

*With linear RJBE changes when plotted as log RJBE vs. log frequency.

Further work must establish the improved form of this function. As noted above, in the 0.2 to 1.0 cps range, acceleration tolerance may actually show a peak, or RJBE may decrease below 0.07 before returning to 1. Between 1 and 20 cps a curve more accurately indicating body resonance may be required. Likewise at some frequency above 100 cps, the tolerance RJBE presumably further decreases, since transmissibility decreases, although skin damage rather than deeper internal discomfort becomes the basis of tolerance estimation.

Unfortunately we are still in an early period of acceleration measurement in which measurements must be analyzed with caution because of the frequency characteristics of the transducers. Certain accelerometers will not respond to frequencies above 20 cps, and others will not respond to frequencies above 30 cps, for example. One can conceive of a "biological acceleration" meter, with a relative jostle biological effectiveness weighting function filter. It can be seen that accelerometers recording the frequency range of 0-20 cps give a better measure of biological tolerance

than those recording just frequencies above 20 cps. Using the "biological acceleration" meter, one could then determine a biological RMS g and a standard deviation $\sigma$ of this RMS g. Then 99.7% of the acceleration peaks important to the biological effect of a time history would fall within the range of the biological RMSg ± 3$\sigma$. This acceleration description may be used with greater ease than one which requires interpretation in terms of a power spectrum. However, until the more precise form of the relative jostle biological effectiveness function can be determined, RMS g values should be specified with an associated power spectrum.

A report by Parks[65] comparing tracking performance while experiencing complex waveform or sinusoidal vibrations suggests some of the ideas developed in this section. He says, "In summary, there is evidence that a transfer function can be found and that data derived with sinusoidal data may be extended to complex patterns of random vibration.....Results of this experiment show that the physical description which could serve this purpose may be a combination of frequency and some factor related to RMS." (i.e. RMS g). Buchmann[12] also reviews the problem of establishing a mathematical means to compare the biological effects of different jostle environments.

## Conclusion

This preliminary study has indicated that pilots can tolerate for at least 100 seconds and carry out some useful control up to at least a jostle level of $0.7g_z$RMS. Training in these environments in techniques of bracing to reduce body and head "slap" and reducing involuntary control input is recommended for these expecting to enter such environments either during normal or emergency operations. Improvements of restraints, displays, and controls could extend man's usefulness in these environments.

## Summary

Problems of terminology of acceleration and flight simulation are reviewed, with a preliminary historical review of particularly moving base flight simulation. The capabilities and limitations of the Navy Johnsville human centrifuge and the North American Aviation (Columbus) "G-seat" for jostle simulation are presented; the latter is more realistic.

For jostle acceleration power spectra peaking near 1 cps, limited flight control could be maintained at a jostle level of $0.35g_z$RMS, equivalent to aircraft response to very severe turbulence, with panel accelerometer readings between -1.2 and $4.0G_z$, maintained for 30 minutes. A jostle of $0.70g_z$RMS, with panel accelerometer readings between -3 and $5.5G_z$, could be tolerated for at least 100 seconds, although with severe but far from complete control loss. For these jostle conditions, tolerance was fatigue limited, due to muscular efforts to stay in place in the cockpit. The torso restraint is inadequate for jostle conditions considerably more severe than those experienced in present aircraft.

Potential developments of restraints, displays, and controls for use in severe jostle environments are noted. A "relative jostle biological effectiveness" concept is suggested for test as a means of comparing the biological effects of jostle environments with different frequency components.

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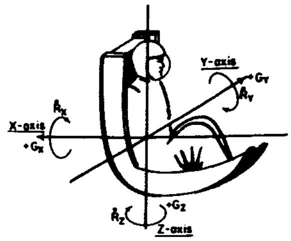
## Addendum

Another pre-World War I moving base flight simulator has come to my attention: the "oscillator", an airplane like devise pivoting on the ground with large control surfaces moved by the pilot in a strong wind, to give him the feel for airplane responses (at small angles of attack). See figure 121 of reference 82.

In the historical vein, it is appropriate to name those instrumental in the first controlling of the Johnsville human centrifuge through a computer, the first high acceleration moving base pilot controlled motion and display flight simulation[17,60] for which the author was "project officer". Aviation Medical Acceleration Laboratory: Dr. John L. Brown, Richard Crosbie, Carter Collins, Dr. Carl Clark. Aeronautical Computer Laboratory: Morris Plotkin, Jay Rabb, Cdr. C. Fink Fischer, Harold Tremblay, Victor Doesch, Harold Doerfel, Edward Loller, Dr. Edward Knobelaugh. Moore School, University of Pennsylvania: Frank Nicholson, William Wachter, Elizabeth Schoff, Dr. Emil Grosswald.

- End -




(Directions Are Those of Heart Displacement, With Respect to the Skeleton)

Linear Acceleration Modes

Description of Heart Motion

| ACTUAL | OTHER DESCRIPTION | | UNIT VECTOR |
|---|---|---|---|
| Towards spine | Eye-balls-in | Chest-to-back | $+G_x$ |
| Towards sternum | Eye-balls-out | Back-to-chest | $-G_x$ |
| Towards feet | Eye-balls-down | Head-to-foot | $+G_z$ |
| Towards head | Eye-balls-up | Foot-to-head | $-G_z$ |
| Towards left | Eye-balls-left | ——— | $+G_Y$ |
| Towards right | Eye-balls-right | ——— | $-G_Y$ |

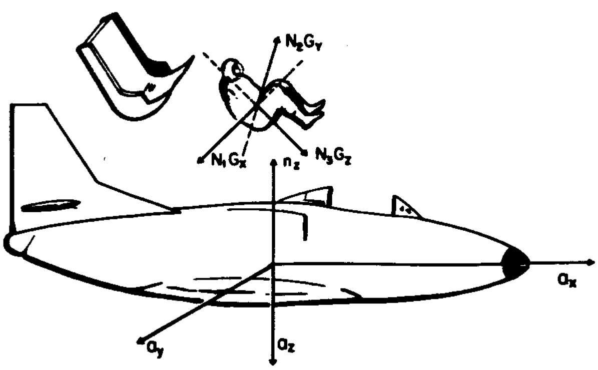
$$NG = \frac{a}{g} = N_1 G_x + N_2 G_Y + N_3 G_z$$

$$N^2 = N_1^2 + N_2^2 + N_3^2$$

Angular Acceleration Modes

| | |
|---|---|
| Acceleration about X-axis (The heart rolls left in the chest) | $+\dot{R}_x$ |
| Acceleration about Y-axis (The heart pitches down) | $+\dot{R}_Y$ |
| Acceleration about Z-axis (The heart yaws left) | $+\dot{R}_z$ |

Figure 1: The physiological acceleration terminology. (Official U. S. Navy photograph)




Linear Acceleration Modes

| Description | | Symbol | |
|---|---|---|---|
| Aircraft | Physiological | Aircraft | Physiological |
| Forward | Supine G | $+a_x$ | $+N_1 G_x$ |
| Backward | Prone G | $-a_x$ | $-N_1 G_x$ |
| Upward | Positive G | $-a_z$ | $+N_3 G_z$ |
| Downward | Negative G | $+a_z$ | $-N_3 G_z$ |
| Straight and level flight at constant speed | | $a_z = 0,\ n_z = 1g$ | $N_3G_z = 1G_z$ |
| To right | Lateral G | $+a_Y$ | $+N_2 G_Y$ |
| To left | Lateral G. | $-a_Y$ | $-N_2 G_Y$ |
| **Angular Acceleration Modes** | | | |
| Roll right | The heart rolls left | $+\dot{p}$ | $+N_4\dot{R}_X$ |
| Pitch up | The heart pitches down | $+\dot{q}$ | $+N_5\dot{R}_Y$ |
| Yaw right | The heart yaws left | $+\dot{r}$ | $-N_6\dot{R}_Z$ |

Figure 2: A comparison of the physiological and NASA aircraft acceleration techniques. (Official U. S. Navy photograph)

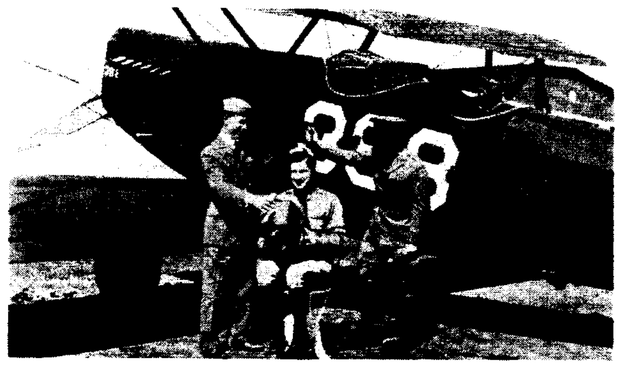


Figure 3: The "instrument box on the turning chair", and airplane with hood for blind flight. (From Isaac Jones: Flying Vistas: The Human Being as Seen Through the Eyes of the Flight Surgeon. J. B. Lippincott Co., Philadelphia, 1937, by permission.

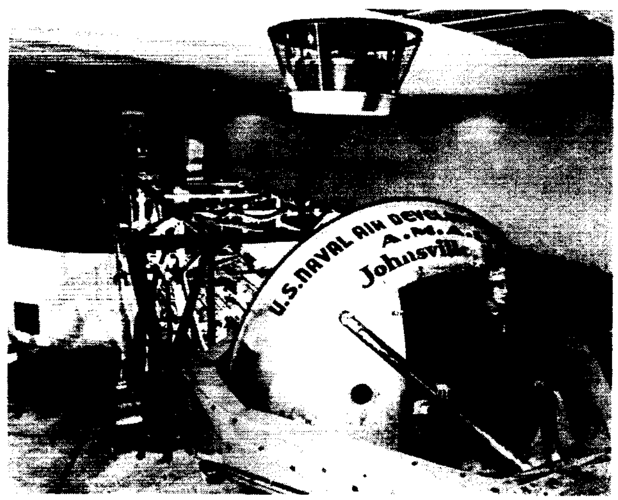



Figure 4: The Navy Johnsville Human Centrifuge. (Official U. S. Navy photograph)

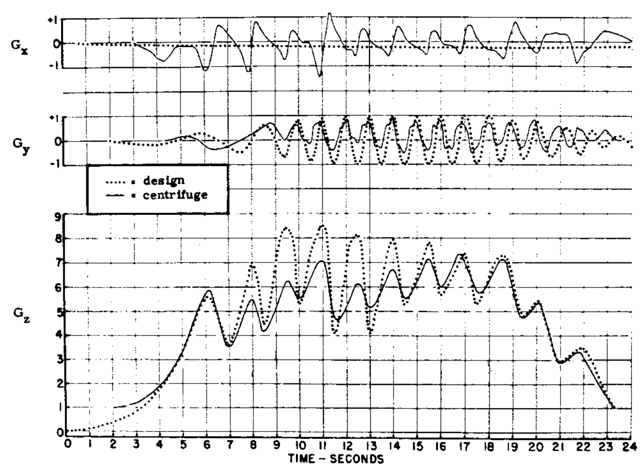



Figure 5: Accelerations computed for an X-15 re-entry with speed brakes closed and pitch damper off, and Navy centrifuge simulation by cam control. (Official U.S. Navy photograph)

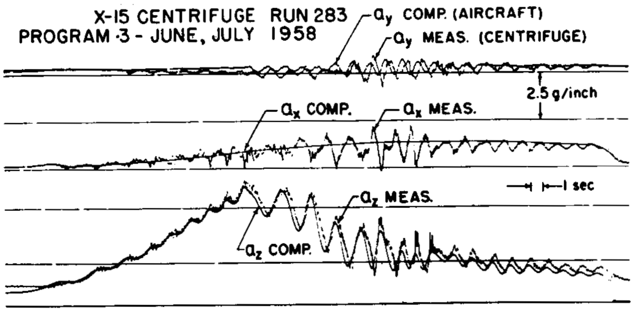



Figure 6: Accelerations computed for an X-15 reentry with dampers off, and Navy centrifuge simulation by pilot-computer control. (Official U. S. Navy photograph).

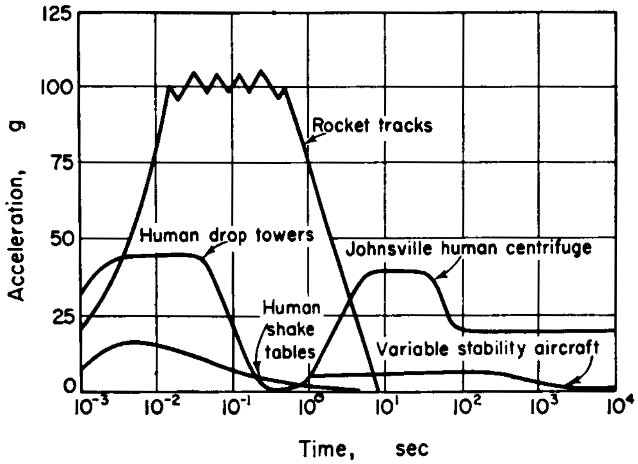



Figure 7: Acceleration vs. time capabilities of various motion simulation devices. (Official U. S. Navy photograph).

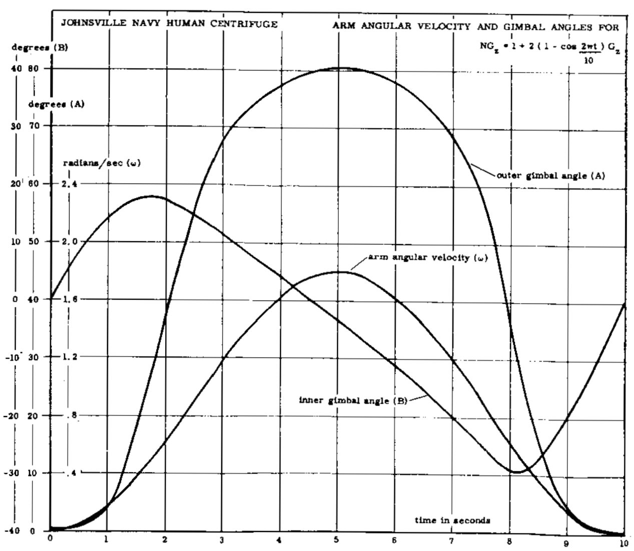



Figure 8: Navy centrifuge gimbal responses for a $5G_z$ peak haversine waveform.

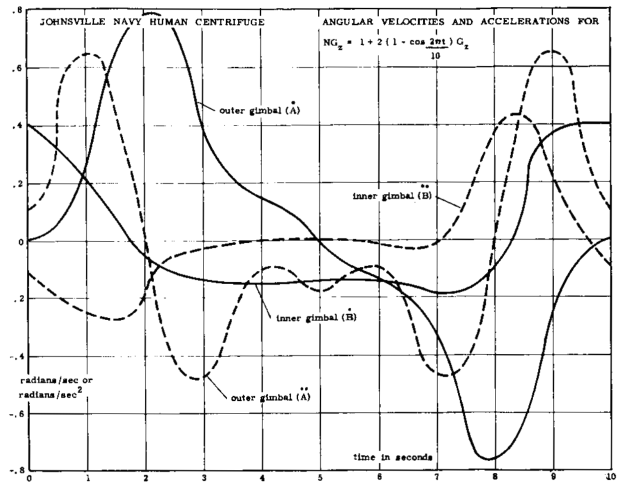



Figure 9: Navy centrifuge gimbal velocities and accelerations for a $5G_z$ peak haversine waveform.

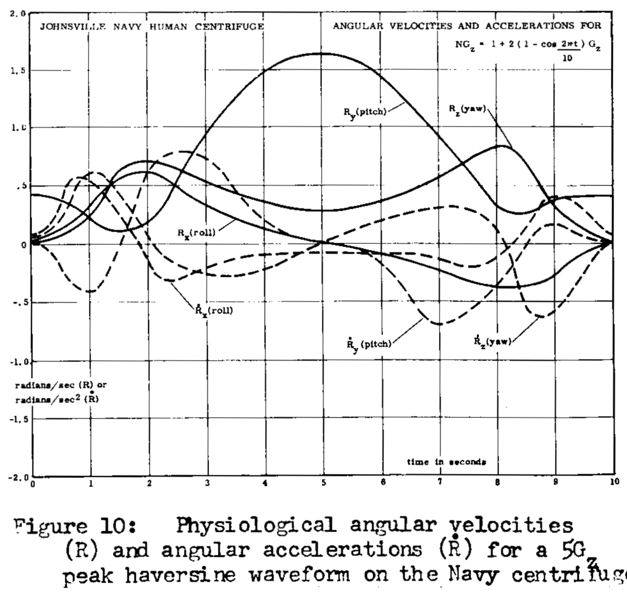



Figure 10: Physiological angular velocities (R) and angular accelerations ($\dot{R}$) for a $5G_z$ peak haversine waveform on the Navy centrifuge.

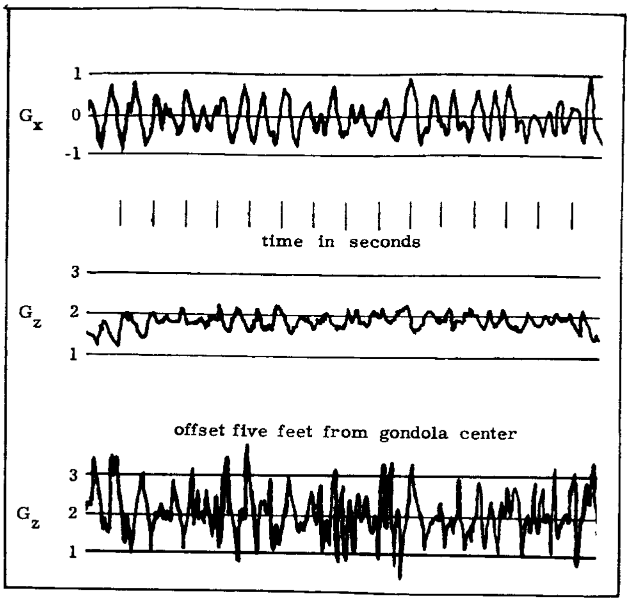



Figure 11: Jostle accelerations with the Navy centrifuge.

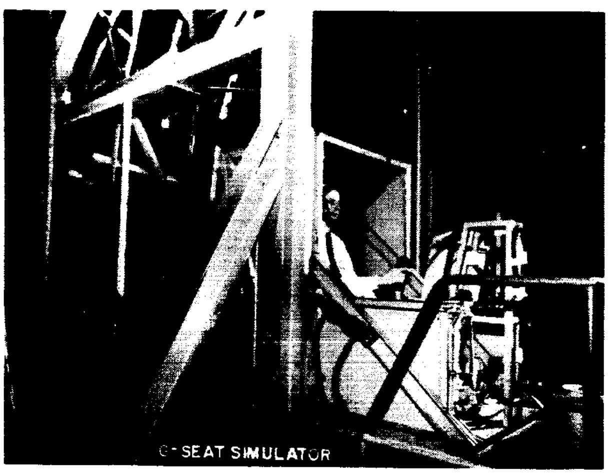



Figure 12. The North American Aviation (Columbus) "G-seat." (Courtesy of North American Aviation, Inc.).

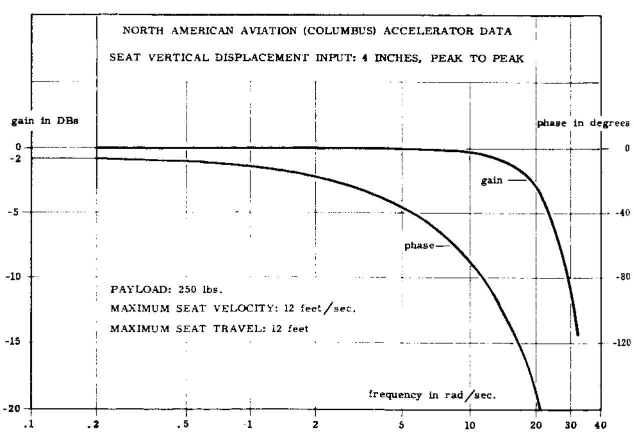



Figure 13: Response capabilities of the G-seat. (Courtesy of North American Aviation, Inc.).

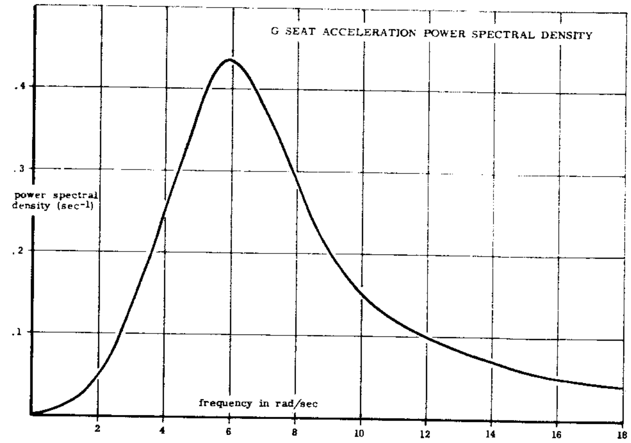



Figure 14: The acceleration power spectral density of this study. (Courtesy of North Amer. Aviation, Inc.)

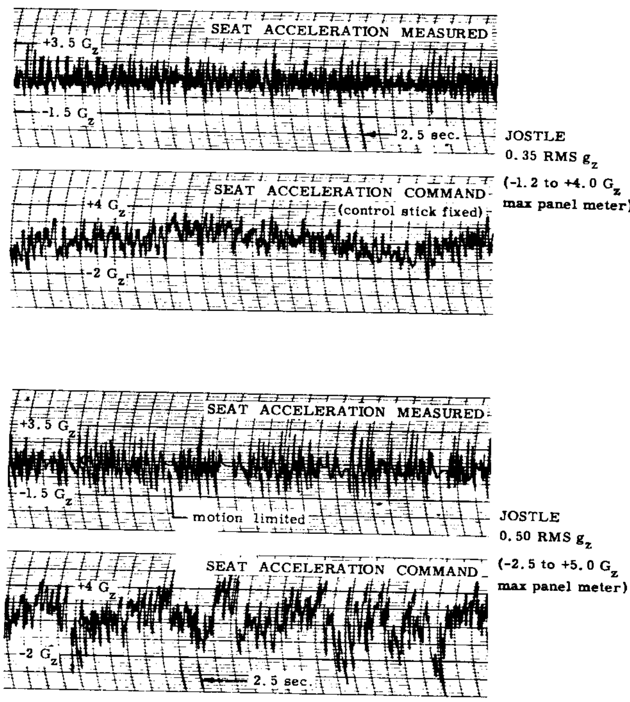



Figure 15: Jostle time histories with the G-seat.

Figure 16: The Navy polyurethane foam restraint. (Official U. S. Navy photograph).

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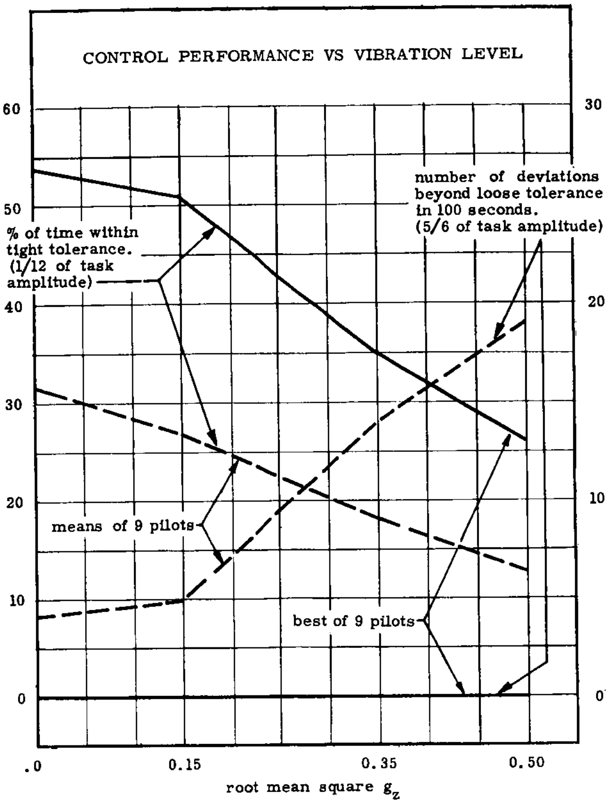


Figure 17: Tracking performance on the G-seat.

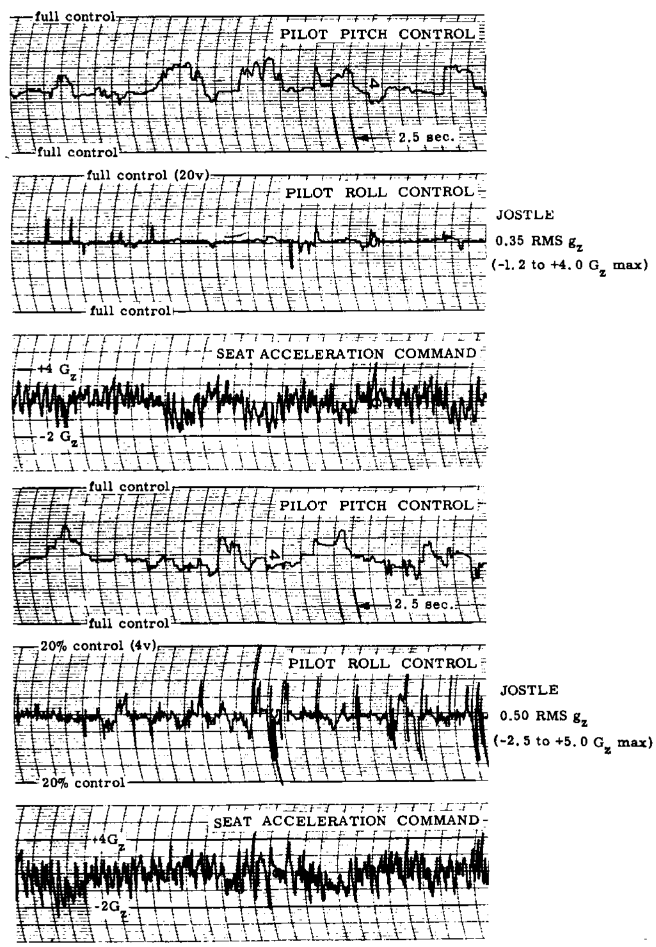


Figure 18: Pilot control responses on the G-seat.

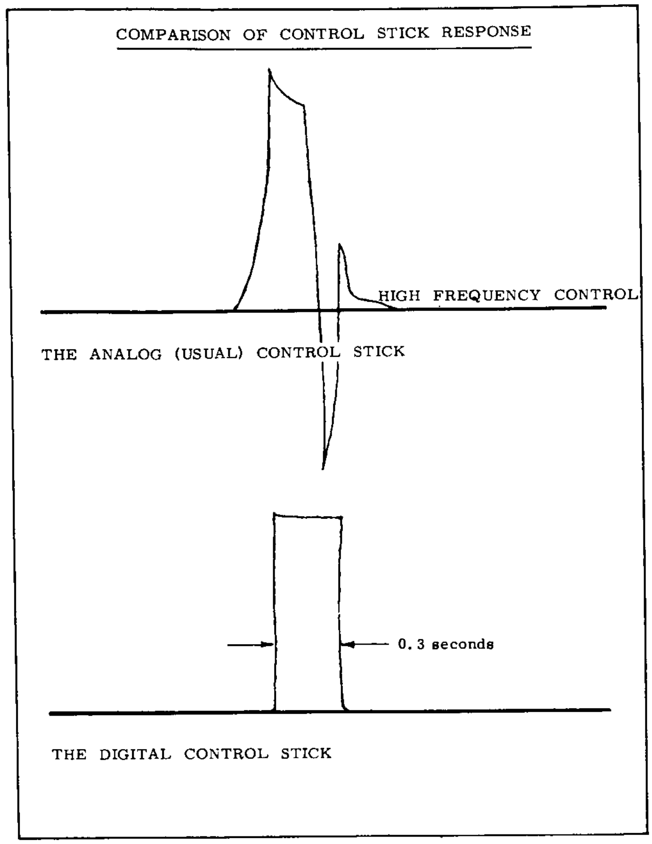


Figure 19: Typical control pulses for the analog and digital controllers.

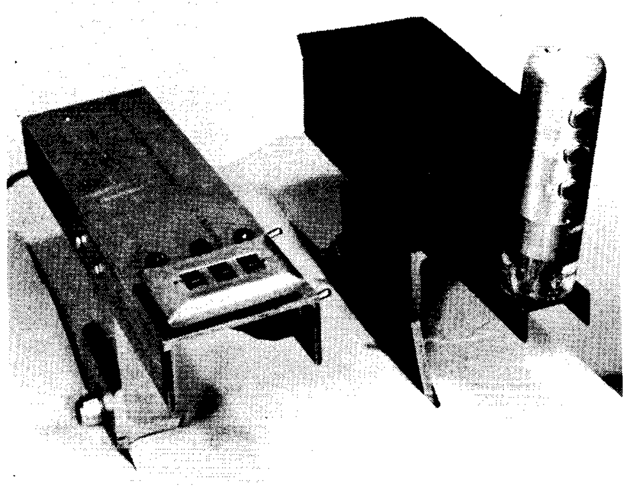

Figure 20: Two early designs of digital (push button) controllers.

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